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13. ABSTRACT *(Maximum 200 words)*

This project has developed provably correct architectures and reconfiguring algorithms for controlling processes whose dynamical models may change drastically due to aging, component failure or other unpredictable events. With AFOSR support, the devising, testing and analysis of a provably correct, "smart." high-level controller called a *supervisor* has been completed. The supervisor is capable of controlling the set-point of a very poorly modelled process by orchestrating the of switching a sequence of candidate, off-the-shelf, linear set-point controllers into feedback with the process. The provable features of the overall supervisory control system include robustness to unmodelled dynamics, noise and disturbances, as well as exponential convergence in the absence of noise. With the ultimate goal of extending these ideas to the supervision of families of nonlinear regulators, it has been shown that the any certainty equivalence control causes the familiar interconnection of a controlled process and associated output estimator to be *detectable* through the estimator's output error, for every frozen value of the index or parameter vector upon which both the estimator and controller dynamics depend. The concept of supervisory control has been successfully applied, both in simulations and in laboratory experiments, to the problem of auto-calibrating a stereo-vision based system for driving a rigid mobile robot to a prescribed target.

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1 Introduction

This is the final technical report on research carried out with the support of AFOSR under Grant F4920-94-1-0181. The report consists of the following sections:

1. Introduction
2. Work Accomplished
3. Publications
4. Individuals Involved in the Research Effort

2 Work Accomplished

With AFOSR support we have prepared and/or published during the three year grant period April 1, 1996 – March 31, 1997, one post workshop volume [1], four full-length technical papers [2] - [5], two full-length plenary review articles [6], [7], one full-length historical paper [8], [9], and eleven conference papers [10] - [20]. Three additional full-length papers will be published this year [21] - [23] and two full-length technical reports [24],[25] and one doctoral thesis [26] are near completion.

Our research has been concerned with the study of a number of different classes of logic-based switching control systems. By a logic-based switching controller is meant a controller whose subsystems include not only familiar dynamical components {integrators, summers, gains, etc.} but logic-driven elements as well. A general overview of this area can be found in [6]. This paper documents the content of a plenary lecture delivered by the P. I. at the Third European Control Conference in September, 1995. The P. I. also organized a workshop on logic-based switching which took place on Block Island, R. I. at the end of September, 1995. Reference [11] discusses a variety of unresolved issues concerned with logic and switching while [1] is a post-workshop volume which discusses a wide range of ideas and applications.

Although logic-based switching control is a broad field with many different lines of inquiry, we've devoted much of our effort to the application of logic-based switching to the following basic problem: Construct a control system capable of driving to and holding at a prescribed set-point r, the output y of a process modeled by a dynamical system with large scale structured uncertainty. Toward this end we've completed basic development, testing and analysis of a "smart," high-level controller called a *supervisor* which is capable of controlling the set-point of a very poorly modelled process by orchestrating the of switching a sequence of candidate, off-the-shelf, set-point controllers into feedback with the process [5], [21]. The supervisory control system

- is very easy to implement. Supervisory control employs logic and control parameter switching rather then dynamical parameter tuning. Switching logics seem to be easier

to implement than dynamical parameter tuners. We've developed a Matlab Simulink implementation of a generic supervisor which can be downloaded to C-code for real-time applications. The supervisor module is available via the World Wide Web.

- is compatible with off-the-shelf, non-adaptive set-point controllers
- is provably correct
- is inherently robust to modeling errors
- does not require a persistently exciting probing signal
- does not require a priori knowledge of disturbance or noise bounds
- does not attempt to estimate disturbance or noise bounds
- cannot be destabilized by noise or disturbance inputs
- performs very well in simulation and laboratory experiments.

Provably correct algorithms for supervising families of discrete-time controllers and families of two-degree-of-freedom controllers can be found in [23] and [3] respectively. In [4] the concept of "cyclic switching" is combined with the architecture described in [5] to deal with unavoidable singularities in parameter space where certainty equivalence control is impossible.

Reference [15] and [13] represent our first attempts to use switching and logic to improve the performance of a linear system, whose norm bound on unmodelled dynamics is uncertain; many of the complexities normally associated with switching vector fields are avoided here by clever use of the Youla parameterization.

At the present time, the only provably correct techniques we know of for dealing with uncertain nonlinear dynamical systems with non-globally Lipschitz nonlinearities, are parameter adaptive methods which employ nonlinear damping and back-stepping. Successful as they have been in dealing with here-to-fore unresolved problems, these concepts are known to result in complicated algorithms which, because of "adaptive zero-canceling," are limited to special types nonlinear systems - e.g., those with stable zero dynamics. In view of the simple structure and inherent robustness of the supervisory control architecture we've been discussing, we've been led to ask if these ideas can be used to advantage in dealing with nonlinear dynamics. References [12], [14] and [19] represent first steps along these lines; in [14] we show that the architecture we've been pursuing can yield semi-global results for a prototype one-dimensional, uncertain nonlinear model. A broad overview of these findings can be found in [7]. This paper documents the content of a plenary lecture delivered by the P. I. at the XI Congresso Brasileiro de Automática in São Paulo, Brazil in September 1996.

Essentially all of our work concerned with the supervision of families of linear and nonlinear controllers, exploits the concept of "certainty equivalence." Certainty equivalence is a

well known heuristic idea which advocates that in an adaptive context, the feedback control to an imprecisely modeled process should, at each instant of time, be designed on the basis of a current estimate of what the process model is, with the understanding that each such estimate is to be viewed as correct even though it may not be. On the surface justification for certainty equivalence seems self-evident: if process model estimates converge to the "true" process model, then a certainty equivalence based controller ought to converge to the nonadaptive controller which would have been implemented had there been no plant uncertainty. The problem with this justification is that because of noise and unmodelled dynamics, process model estimates don't typically converge to the true process model - even in those instances where certainty equivalence controls can be shown to perform in a satisfactory manner. A more convincing justification stems from the fact that any {stabilizing} certainty equivalence control causes the familiar interconnection of a controlled process and associated output estimator to be *detectable* through the estimator's output error e_p, for every frozen value of the index or parameter vector p upon which both the estimator and controller dynamics depend. Detectability is key because adaptive controller tuning/switching algorithms are invariably designed to make e_p small - and so with detectability, smallness of e_p ensures smallness of the state of the controlled process and estimator interconnection. The fact that certainty equivalence implies detectability has been known for some time - this has been shown to be so whenever the process model is linear and the controller and estimator models are also linear for every frozen value of p. In [24] use is made of recently introduced concepts of input-to-state stability and detectability [6] for nonlinear systems, to prove that the same implication is valid in a more general, nonlinear setting.

We've studied the potential applicability of logic-based switching and supervision to problems in computer vision and especially vision-based control [2] [16], [20]. One of the specific problems undertaken was to develop the results needed to apply supervisory control to the problem of auto-calibrating a stereo vision-based, set-point tracking control system. One of the technical issues which arises in this context is to prove, for a particular state dependent matrix J which is always singular, and a tracking error e, that $Je = 0$ implies $e = 0$; by appealing to the underlying geometry of the vision system being considered, we've been able to show that this is in fact so [26]. This finding proves for the first time, that image-based motion control of a mobile robot to a fixed target will in fact accomplish the positioning task. This finding paves the way for the development of a correctness proof for a switching logic and architecture devised to calibrate and re-calibrate on the fly, a closed-loop camera navigation system for a mobile robot. The system of interest is described in [16]. In this paper, a robot-video camera system is modelled as a linear system with an unknown but slowly varying coefficient matrix. Because the slowly varying coefficient matrix is actually a state-dependent Jacobian matrix, the results obtained are valid only for slowly moving robots. Reference [20] seeks to overcome this limitation by using actual nonlinear camera models. Because camera models depend nonlinearly on camera parameters, the development of an algorithm capable of calibrating on-line using real operating data, is intractable. One way to side-step the tractability problem, is to restrict the uncertainty to a finite but large number of possible models. This is the approach taken in this paper.

Even with a finite number of candidate camera models, the self-calibration problem remains formidable, because each such model is nonlinear and because the number of candidate models is initially large. The basic approach taken is to use an estimator-based supervisor together with a certainty equivalence control. In addition, to shrink the uncertainty, falsification {a form of model invalidation} is used together with a well-known algebraic relation from computer vision called the "epipolar constraint" to enable the supervisor to eliminate over time unpromising candidate camera models. What results proves to be a semi-global stable system.

3 Publications

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[26] Wen-Chung Chang. *Vision-Based Control of Uncertain Systems.* PhD thesis, Yale University, 1997.

4 Individuals Involved in the Research Effort

1. A. S. Morse, Principal Investigator
2. W-C Chang, Graduate Student
3. J. P. Hespanha, Graduate Student
4. D. Borrelli, Visiting Graduate Student
5. Shogo Fujji, Visiting Graduate Student
6. G. D. Hager, Faculty
7. E. Mosca, Faculty at University of Florence